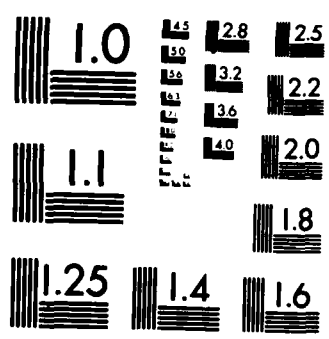


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DEPARTMENT OF ELECTRICAL ENGINEERING
University of Washington
Seattle, WA 98195

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Final Report

by

Akira Ishimaru

November 1984

MULTIPLE SCATTERING EFFECTS ON TRANSMISSION THROUGH THE ATMOSPHERE

ONR Contract N00014-78-C-0723

September 1, 1978 to August 31, 1984

Dr. B. R. Junker, Contract Monitor
Code 421
Director, Physics Program
Physical Sciences Division
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This final report gives a summary of the work completed on the contract covering the period from September 1, 1978 to August 31, 1984. The work is directed to the investigation of the transmission characteristics of optical waves with wavelengths in the range of 1-15 μ m through various atmospheric conditions including clouds, fog, turbulence, rain, hail, snow, and inhomogeneous layers.		

1. Principal Investigator: Akira Ishimaru

2. Contract Description

This contract is directed to the investigation of the transmission characteristics of a wave with the wavelengths in the range of $1\text{ }\mu\text{m}$ to $15\text{ }\mu\text{m}$ through various atmospheric conditions including clouds, fog, turbulence, rain, hail, snow, and inhomogeneous layers.

3. Summary of Progress

Optical propagation in the atmosphere is greatly affected by various particulate matter such as clouds, fog, rain, hail, snow, turbulence, and inhomogeneous layers. Our study has been centered on the wave characteristics in particulate matter. Our progress in this area includes the following:

(a) Pulse Propagation and Scattering in Particulate Matter [1-3,5,6,11]

Pulse broadening due to various particulate matter in the atmosphere is important in determining the data transmission rate of communications. We have conducted fundamental studies on this problem. The backscattering of pulses from discrete scatterers is experimentally and theoretically studied [1]. A theoretical study on the backscattering of a pulse from turbulence is made using small angle approximations [2]. It was observed experimentally [3] that the diffused pulse propagates with a reduced speed. A general summary of the pulse problems is given in [5] and [6]. More refined pulse experiments are reported in [11].

(b) Coherent Wave Propagation in Discrete Scatterers [7,10,13]

One of the fundamental questions relating to the wave propagation in discrete scatterers is the determination of the propagation constant for the average (coherent) field. For a tenuous medium, the propagation constant is given by the classic Van de Hulst formula. However, when the volume density is one percent or higher, the propagation constant is not linearly dependent on the density. There have been extensive theoretical investigations on these multiple scattering effects. We made the first detailed controlled experimental study [7,10,13] using optical and ultrasound scattering techniques. We have thus established an important and useful benchmark for further theoretical study.

(c) Incoherent Wave Characteristics [4,8,9]

The wave in discrete scatterers may be classified into "coherent" and "incoherent" waves. The incoherent field is responsible for backscattering, depolarization, and diffusion. We have carefully examined these multiple scattering effects due to rain [4] and due to fog [8]. We have made careful experimental studies of a beam wave and compared them with the diffusion theory and the first-order scattering theory [9].

(d) Backscattering Enhancement [12]

Backscattering is important in radar and lidar applications. We observed a sharp peak of the order of 1 degree or less in the backscattering direction [12]. This appears to be caused by the second- and higher-order multiple scattering and the coherent length of the order of the mean free path. This interesting phenomenon may be potentially important in practical applications. We are continuing the detailed study of this effect.

4. Publications

Journal Publications with ONR Sponsorship

1. "Backscattering of a picosecond pulse from densely distributed scatterers," Applied Optics, 18:20, pp. 3484-3488, October 1979; coauthors, K. Shimizu, L. Reynolds, and A. P. Bruckner.
2. "Backscattered pulse shape due to small-angle multiple scattering in random media," Radio Science, 15:1, pp. 87-93, January-February, 1980; coauthor, K. J. Painter.
3. "An experimental test of the reduced effective velocity of light in a diffuse medium," Optics Letters, 5:5, pp. 205-207, May 1980; coauthor, K. Shimizu.
4. "Multiple scattering effects on wave propagation due to rain," Annales des Télécommunications, 35, pp. 373-379, November-December 1980; coauthor, R. Cheung.
5. "Theory of optical propagation in the atmosphere," Optical Engineering, 20:1, pp. 63-70, January-February 1981.
6. "Theoretical and experimental study of transient phenomena in random media," Proceedings, Symposium on Multiple Scattering and Waves in Random Media, ed. by P. L. Chow, W. Kohler, and G. Papanicolaou. North-Holland Publishing Co., Amsterdam, 1981.
7. "Attenuation constant of coherent field in a dense distribution of particles," Journal of the Optical Society of America, 72:10, pp. 1317-1320, October 1982, coauthor, Y. Kuga.
8. "Transmission, backscattering, and depolarization of waves in randomly distributed spherical particles," Applied Optics, 21:20, pp. 3792-3798, October 1982; coauthor, R. Cheung.
9. "Scattering and diffusion of a beam wave in randomly distributed scatterers," Journal of the Optical Society of America, 73:2, pp. 131-136, February 1983; coauthors, Y. Kuga, R. Cheung, and K. Shimizu.
10. "Acoustic wave propagation in randomly distributed spherical particles," Journal of the Acoustical Society of America, 74:5, pp. 1529-1534, November 1983; coauthors, João Carlos Machado and Rubens A. Sigleemann.
11. "Experiments on picosecond pulse propagation in a diffuse medium," Journal of the Optical Society of America, 73:12, pp. 1812-1815, December 1983; coauthors, Y. Kuga and A. P. Bruckner.
12. "Retroreflectance from a dense distribution of spherical particles," Journal of the Optical Society of America A, 1:8, pp. 831-835, August 1984; coauthor, Y. Kuga.
13. "Acoustic coherent wave propagation in a dense concentration of scatterers," submitted to the Journal of the Acoustic Society of America.

4. Publications - continued

Paper Presentations Related to the Contract Since September 1978

1. A. Ishimaru, "Optical scattering and diffusion in turbulence and scatterers," OSA Meeting, San Francisco, October 1978.
2. K. Shimizu and A. Ishimaru, "Estimation of size distribution of randomly distributed scatterers," OSA Meeting, San Francisco, October 1978.
3. A. Ishimaru, "Forward scatter and diffusion of pulses in a random distribution of scatterers," URSI Meeting, Boulder, November 1978.
4. A. Ishimaru, "Multiple scattering effects on pulse propagation through fog and clouds," Naval Ocean Systems Center Program Review, San Diego, November 1978.
5. A. Ishimaru, "Forward scatter theory and diffusion theory for wave in random media," Bremmer Session, National Radio Science Meeting, Seattle, June 1979.
6. A. Ishimaru, "Multiple scattering effects on backscattering of a pulse from terrain," National Radio Science Meeting, Seattle, June 1979.
7. K. J. Painter and A. Ishimaru, "Backscattered pulse shape due to small-angle multiple scattering from a slab of random medium," National Radio Science Meeting, Seattle, June 1979.
8. K. Shimizu, A. Ishimaru, and A. P. Bruckner, "Backscattering of a picosecond pulse from a dense scattering medium," National Radio Science Meeting, Seattle, June 1979.
9. R. L.-T. Cheung and A. Ishimaru, "Multiple scattering of millimeter waves in rain," National Radio Science Meeting, Seattle, June 1979.
10. A. Ishimaru was invited to speak at the Chemical Systems Laboratory Scientific Conference on Obscuration and Aerosol Research, U.S. Army, Aberdeen Proving Ground, Maryland, September 1979.
11. K. Shimizu, A. Ishimaru, and L. Reynolds, "Diffusion and scattering of a picosecond pulse in a dense scattering medium," OSA Meeting, Rochester, October 1979.
12. A. Ishimaru was invited to speak on "Theoretical and experimental study of transient phenomena in random media" at the workshop on "Wave Propagation in Turbulent Media" sponsored by the Mathematics Division, U.S. Army Research Office, at Virginia Polytechnic Institute, Virginia, March 24-27, 1980.

4. Publications - continued

Paper Presentations Related to the Contract Since September 1978

13. A. Ishimaru and R. L.-T. Cheung, "Multiple scattering effects on wave propagation due to rain," URSI Commission F Symposium, Lennoxville, Canada, May 1980.
14. A. Ishimaru, R. L.-T. Cheung, and Y. Kuga, "Diffusion of a beam wave in random discrete scatterers," North American Radio Science Meeting, Quebec, June 1980.
15. A. Ishimaru, "Characterization and remote-sensing of terrain," ICC '80, Seattle, June 1980.
16. A. Ishimaru, "Pulse propagation and diffusion in random media," International URSI Symposium on Electromagnetic Waves, Munich, August 1980.
17. A. Ishimaru and R. L.-T. Cheung, "Incoherent intensities due to rain," National Radio Science Meeting, Boulder, January 1981.
18. A. Ishimaru, "Multiple scattering effects on optical propagation in turbulence and particles," NATO-AGARD Meeting, Monterey, California, April 1981.
19. Y. Kuga and A. Ishimaru, "Attenuation constant of coherent field in dense spherical particles," National Radio Science Meeting, Los Angeles, June 1981.
20. R. L.-T. Cheung and A. Ishimaru, "Transmission and backscattering of optical waves through fog," National Radio Science Meeting, Los Angeles, June 1981.
21. A. Ishimaru, "Multiple scattering in turbulence, scatterers, and rough surfaces," URSI Symposium on Mathematical Models of Radio Propagation, Washington, DC, August 1981.
22. R. L.-T. Cheung, "Millimeter and optical waves in rain and fog," Ph.D. Dissertation, Electrical Engineering Department, University of Washington, December 1981.
23. A. Ishimaru and R. L.-T. Cheung, "Transmission, backscattering, and depolarization of waves in randomly distributed spherical particles," National Radio Science Meeting, Albuquerque, May 1982.
24. A. Ishimaru, "Frequency spectra of ultrasound pulses reflected from scattering medium," 7th International Symposium on Ultrasonic Imaging and Tissue Characterization, NBS, Gaithersburg, Maryland, June 1982.

4. Publications - continued

Paper Presentations Related to the Contract Since September 1978

25. J. Machado, R. A. Sigelmann, and A. Ishimaru, "Experimental and theoretical study of phase and amplitude of ultrasonic waves through random medium," 7th International Symposium on Ultrasonic Imaging and Tissue Characterization, NBS, Gaithersburg, Maryland, June 1982.
26. A. Ishimaru, "Introduction to the theory and application of wave propagation and scattering in random media," SPIE (International Society for Optical Engineering) Meeting on Applications of Mathematics in Modern Optics, San Diego, August 1982.
27. A. Ishimaru, "Scattering of Electromagnetic Waves in a Random Distribution of Nonspherical Particles," International URSI Symposium on Electromagnetic Theory, Santiago de Compostela, Spain, August 1983.
28. A. Ishimaru, "The radiative transfer approach in electromagnetic imaging," NATO Advanced Research Workshop on "Inverse Methods in Electromagnetic Imaging," Bad Windsheim, Federal Republic of Germany, September 1983.
29. A. Ishimaru, "Vector multiple scattering theory for nonspherical particles," OSA Meeting, New Orleans, October 1983.
30. J. C. Machado, R. A. Sigelmann, and A. Ishimaru, "Ultrasound and propagation in randomly distributed particles," ASA Meeting, San Diego, November 1983.
31. D. R. Jackson, D. P. Winebrenner, and A. Ishimaru, "Application of the composite roughness model to bottom backscattering," ASA Meeting, San Diego, November 1983.
32. Y. Kuga and A. Ishimaru, "Retroreflectance from a dense distribution of spherical particles," National Radio Science Meeting, Boulder, Colorado, January 1984.
33. D. Winebrenner and A. Ishimaru, "Rough surface scattering based on the extinction theorem," National Radio Science Meeting, Boulder Colorado, January 1984.
34. A. Ishimaru, "Some current and outstanding problems for waves in random discrete scatterers," National Radio Science Meeting, Boulder, Colorado, January 1984.
35. D. Winebrenner and A. Ishimaru, "Perturbation theory for scattering from random rough surfaces using the extended boundary condition," ASA Meeting, Norfolk, Virginia, May 1984.

4. Publications - continued

Paper Presentations Related to the Contract Since September 1978

36. A. Ishimaru, D. Lesselier, and C. Yeh, "Application of the radiative transfer theory to the multiple scattering by low- and high-loss nonspherical particles," IEEE/AP-S Symposium and National Radio Science Meeting, Boston, Massachusetts, June 1984.
37. A. Ishimaru, "Diffusion approximation of time-dependent transport equation," SIAM Meeting, Seattle, Washington, July 1984.
38. A. Ishimaru and L. Tsang, "Wave theory and radiative transfer theory for discrete scatterers," XXIst General Assembly of URSI, Florence, Italy, August 1984.
39. R. L.-T. Cheung, "Millimeter and optical waves in rain and fog," Ph.D. Dissertation, Electrical Engineering Department, University of Washington, December 1981.
40. Y. Kuga, "Experimental and theoretical studies of the laser light propagation and scattering in a dense distribution of spherical particles," Ph.D. Dissertation, Electrical Engineering Department, University of Washington, July 1983.
41. J. C. Machado, "Experimental and theoretical investigations of propagation and scattering of ultrasound in randomly distributed spherical particles," Ph.D. Dissertation, Electrical Engineering Department, University of Washington, July 1983.

5. Personnel

Graduate Students:

- (a) Koichi Shimizu
- (b) Raymond Chan
- (c) João Machado
- (d) Kirk Painter
- (e) Rudolf Cheung
- (f) Yasuo Kuga
- (g) H. W. Chang

6. Graduate Students Who Have Earned Advanced Degrees

- (a) Kirk Painter, M.S. in E.E., Fall 1978
- (b) Koichi Shimizu, Ph.D. in E.E., Summer 1979
- (c) Raymond Chan, M.S. in E.E., Fall 1980
- (d) Rudolf Cheung, Ph.D. in E.E., Fall 1981
- (e) Yasuo Kuga, Ph.D. in E.E., Fall 1983
- (f) João Machado, Ph.D. in E.E., Fall 1983

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